XMM-Newton Observations of Unidentified Gamma-Ray Objects

- New Results in X-ray Astronomy, MSSL, 11th July 2006 -

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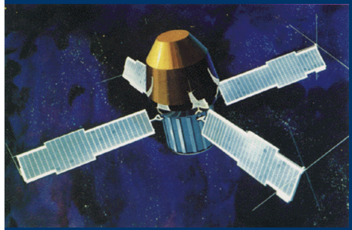
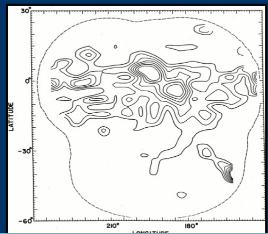
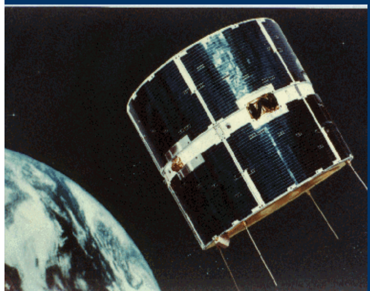
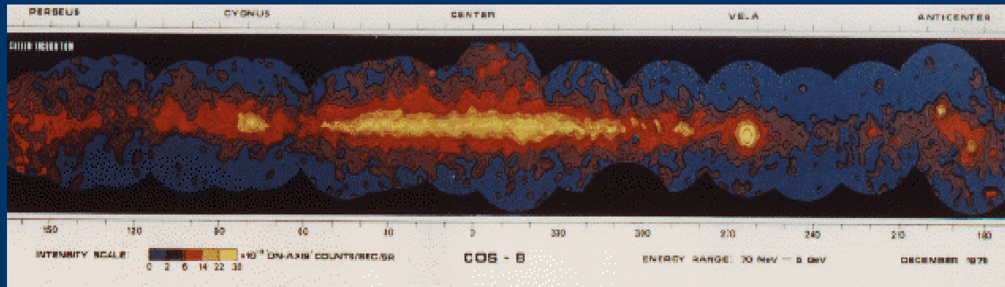
Gamma Ray Sources ID History



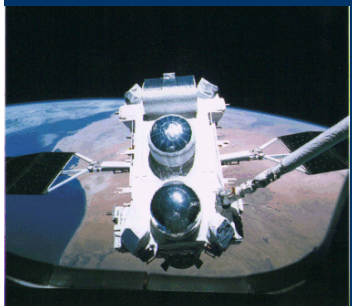


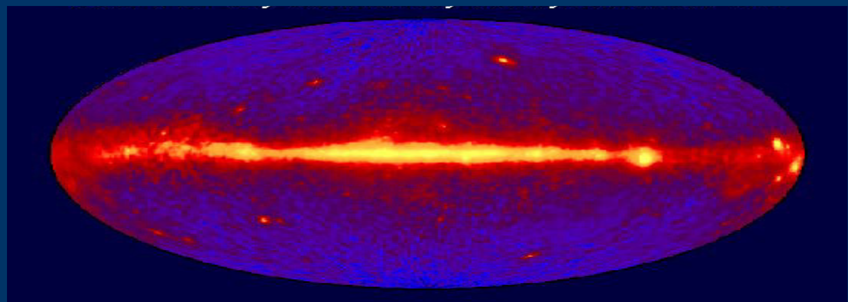
SAS-2 (1972-1973): 3 γ-ray sources detected, 2 identified





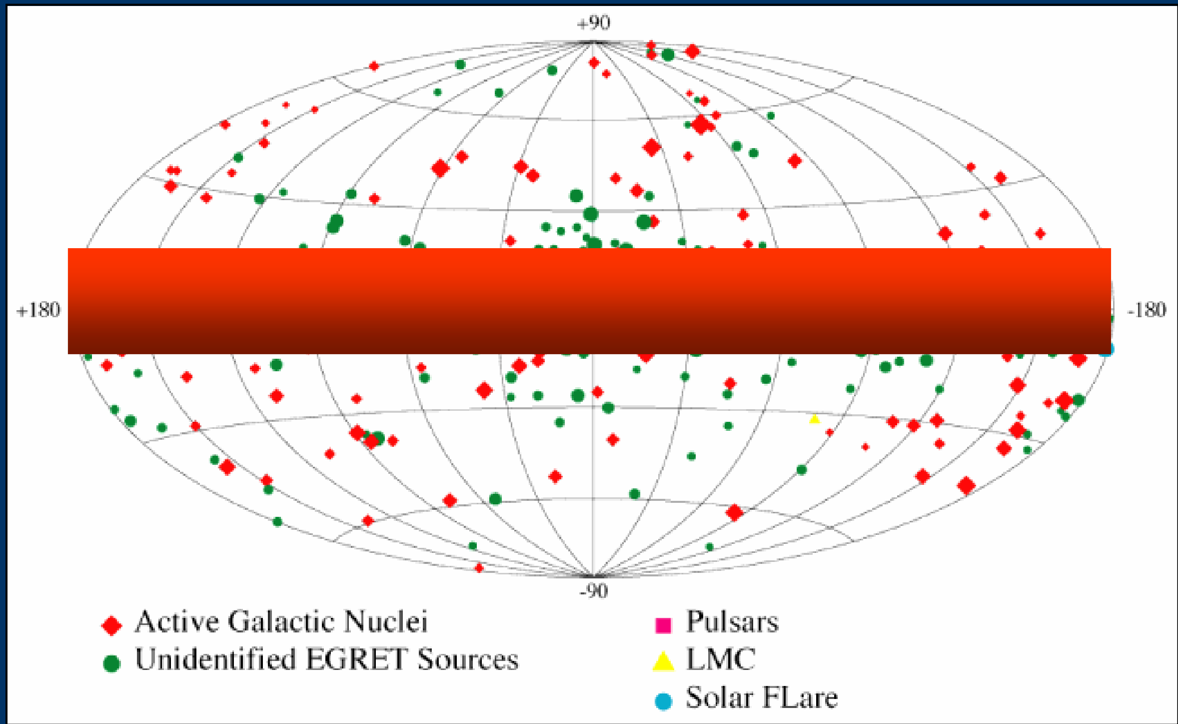
COS-B (1975-1982): 5 γ-ray sources detected, 3 identified





GRO (1991-2000): 271 γ-ray sources detected, 96 identified

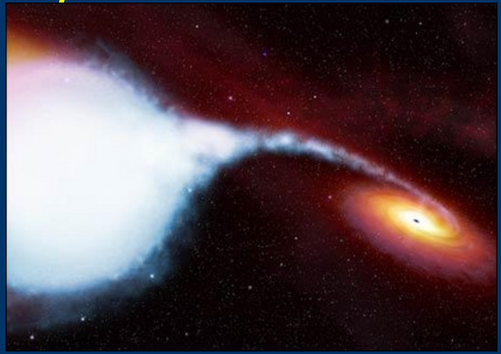
The Unidentified Gamma-ray Objects (UGOs) Population

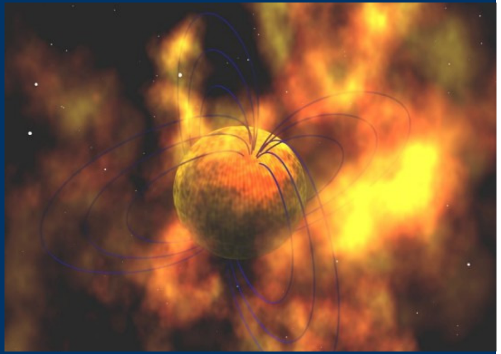


- The majority of the 3EG gamma-ray objects are still unidentified
- ≈ 50% of high-latitude UGOs are identified, mostly associated with AGNs
- ≈ 10% of low-latitude UGOs are identified, mostly associated with PSRs

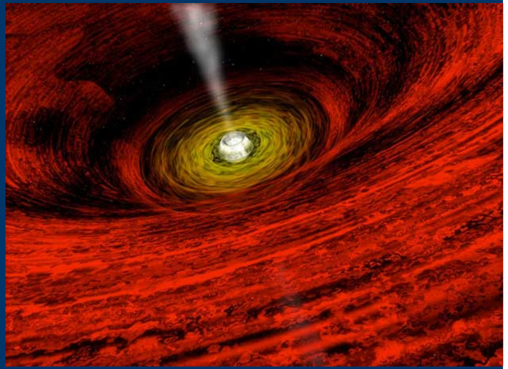
Possible IDs of Galactic UGOs

- The nature of low-latitude UGOs is unclear
- Candidates: SNRs, MicroQuasars, X-ray Binaries, Pulsars, Undiscovered





MicroQuasars:
3EG J1824-1514 (Mc Swain et al. 2004)
3EG J0241+6103 (Casares et al. 2005)
3EG J1639-4702 (Combi 2004) - ?



Pulsars (?):
3EG J0222+4253 (Kuiper et al. 2002)
3EG J1048-5840 (Kaspi et al. 2000)
3EG J2021+3716 (Roberts et al. 2002)
3EG J2227+6122 (Halpern et al. 2001)
3EG J1420-6038 (D'Amico et al. 2001)
3EG J1837-0606 (D'Amico et al. 2001)
3EG J1013-5915 (Camilo et al. 2001)

X-ray Binaries (?):
3EG J0634+0521 (Kaaret et al. 2000)
3EG J0542+2610 (Romero et al. 2001)

UGOs-PSRs connection

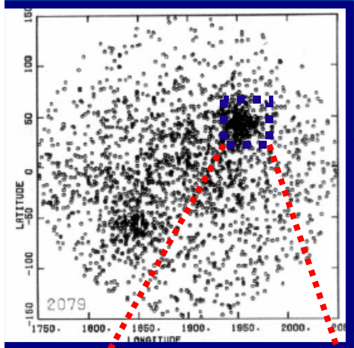
- PSRs are still the most likely counterparts to low-latitude UGOs
- Unfortunately, ID via gamma-ray timing is difficult:

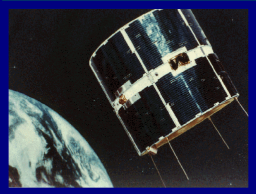
  -Less Photons hamper blind searches via FFT
  -Lack of a reference period for light curve folding
  -Large Error Boxes → Bad Timing accuracy
  -Uncertain source position (< 1 deg) → Δt (ms) ~ 2.3 $\Delta r''$
  -Uncertain correction to SSB

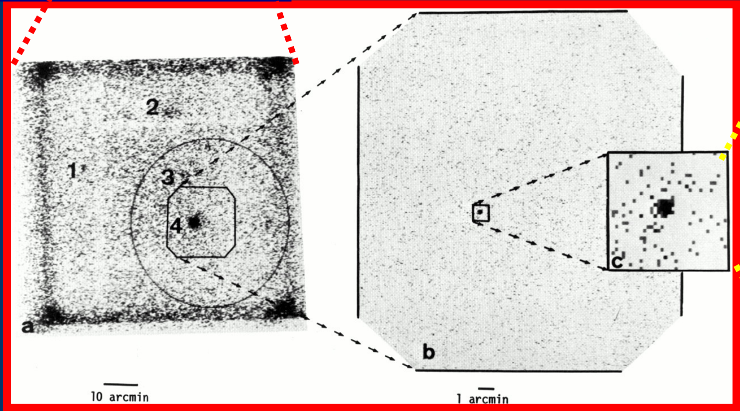
- Step-by-Step Multi-Wavelength approach is the only way

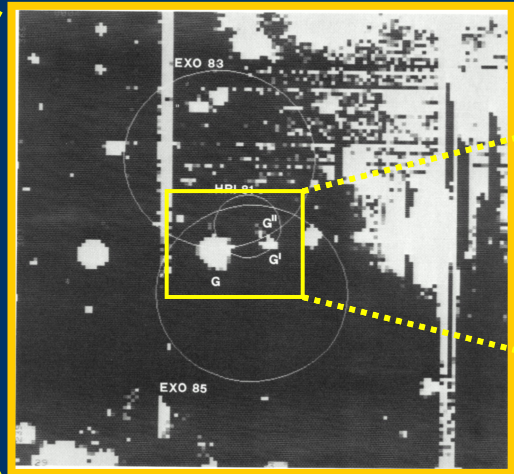
  -Search for possible X-ray counterparts
  -Optical identification of possible X-ray counterparts
  -Select X-ray sources with no (bright) optical counterpart, supposed to be Isolated Neutron Stars (INSs)

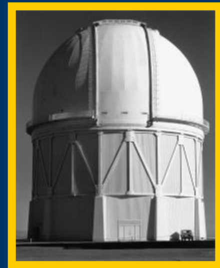
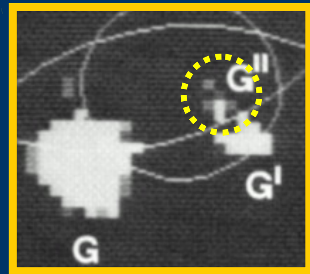
"The Geminga Approach"





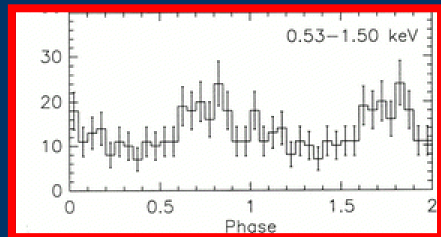


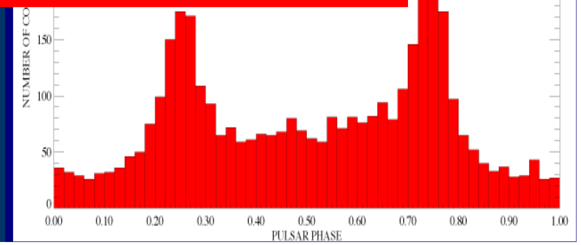


- EINSTEIN/IPC mapping of the COS-B error box → X-ray counterpart
- EINSTEIN/HRI follow-up → Better Position
- Optical counterpart *G"* detected with the CFHT
- $L_\gamma / L_X \approx 1000$ + $L_X/L_{opt} \approx 1000$ ~ Vela Pulsar → INS

- Discovery of X-ray and γ-ray pulsations (237 ms) with ROSAT and GRO





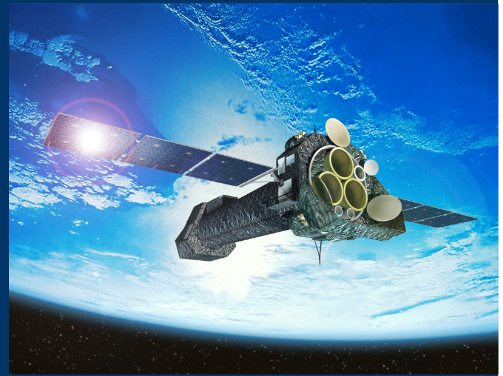
3EG J0616-3310 & 3EG J1249-8330

- Pilot project carried out on two unidentified EGRET sources

•Not **too low** gal lat to avoid galactic plane confusion
•Not **too high** gal lat to minimize AGN contamination

•No radio counterparts

•Relatively bright: Fγ (>100 Mev) ~ 13-20 x 10-8 ph cm^{-2} s^{-1}
•Pulsar-like spectral shape: photon index Γ~ 2.1
•No evidence for gamma-ray variability
•Good Positioning ~ 0.65 degrees radius



X-ray Observations

- X-ray coverage of the two EGRET error boxes with XMM
- 4xEPIC pointings (~10 ks) per EGRET error box

Obs. ID	Rev.	Date (UT)	Pointing Coordinates R.A. (J2000) h m s	DEC (J2000) ° ' "	Exposure Time (ks) PN	MOS1	MOS2	N_H ($10^{20} cm^{-2}$)	Detected Sources
1	346	2001-10-29T17:04:09	06 17 47.1	−32 55 13.9	6.8	11.4	11.5	2.7	50
2	341	2001-10-18T23:53:02	06 17 47.1	−33 25 13.9	6.7	12.0	12.0	2.5	37
3	346	2001-10-29T04:27:17	06 15 24.1	−33 25 13.9	2.5	7.3	7.7	2.4	32
4	346	2001-10-28T23:26:57	06 15 24.1	−32 55 13.9	1.3	6.3	7.7	2.5	27
5	236	2001-03-23T12:56:43	12 57 53.1	−83 15 01.9	7.0	11.2	11.3	10.2	38
6	236	2001-03-23T17:54:20	12 57 53.1	−83 45 01.9	8.2	11.2	10.9	8.4	51
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	239	2001-03-29T22:28:14	12 40 13.1	−83 15 01.9	8.3	12.7	12.9	11.2	52

- Problems with pointing #7 due to high particle background
- Observations described in La Palombara et al. (2004); La Palombara, Caraveo, Mignani et al. (2005)

X-ray Data Analysis

- X-ray data reduction using the Standard Analysys Software (SAS)
  - Hot, flickering pixels, bad columns removed
  - Cosmic rays cleaning
  - Rejection of Time Intervals affectd by high background
  - Selection of Good Time Intervals (GTI)
  - Exposure maps generate to account for QE, vignetting, exposure

- X-ray Catalogue production
  - EPIC PN+MOS1,2 event files merged to increase S/N (spatial binning 4.35")
  - X-ray Source Extraction in 2 Coarse + 5 Fine energy bands
  - Minimum Detection Likelihood: -ln P > 8.5 in at least one energy band

3EG 0616-3310: 146 X-ray sources down to $F_{(0.5\text{-}2\ Kev)} \sim 4 \times 10^{-15}$ erg cm^{-2} s^{-1}

3EG 1249-8330: 148 X-ray sources down to $F_{(0.5\text{-}2\ Kev)} \sim 4 \times 10^{-15}$ erg cm^{-2} s^{-1}

- X-ray Spectral Analysis
  - The short exposure time does not yield enough counts for spectral fitting
  - Spectral information from the Hardness Ratios (HRs) over 7 energy bands
  - Measured HRs compared with simulated HRs for two spectral models: thermal bremsstrahlung (kT=0.5, 1, 2, 5) and power-law (Γ=1, 1.5, 2, 2.5)

Optical Observations

- Optical (BVRI) coverage with the 4x2 CCDs ESO 2.2m/WFI
- Additional BRI with GSC2.3 and JHK with 2MASS

Date dd.mm.yyyy	Obs. ID	Filter Name	Num. of Frames	Exposure Time (s)	Average Seeing	Average Airmass
06.03.2002	2	U	5	2500.0	0.76	1.15
06.03.2002	2	B	5	1500.0	0.68	1.28
10.02.2002	2	V	5	2000.0	0.71	1.30
05.03.2002	3	U	5	2500.0	0.57	1.14
10.02.2002	3	V	5	2000.0	0.00	1.16
05.03.2002	3	R	5	2000.0	0.85	1.05
08.03.2002	3	I	13	3250.0	0.92	1.18
05.03.2002	4	U	5	2500.0	0.87	1.30
12.12.2001	4	B	5	1500.0	0.97	1.05
12.12.2001	4	V	5	2000.0	1.03	1.01
12.12.2001	4	R	5	2000.0	0.89	1.11

- (WFIx5)x4x4 pointings per EGRET error box (FOV ≈ 0.5x0.5 deg ≈ EPIC)
- Observations executed in Service Mode
- Not all pointings completed due to bad weather and scheduling constraints
- Error box of 3EG 1249-8330 poorly covered

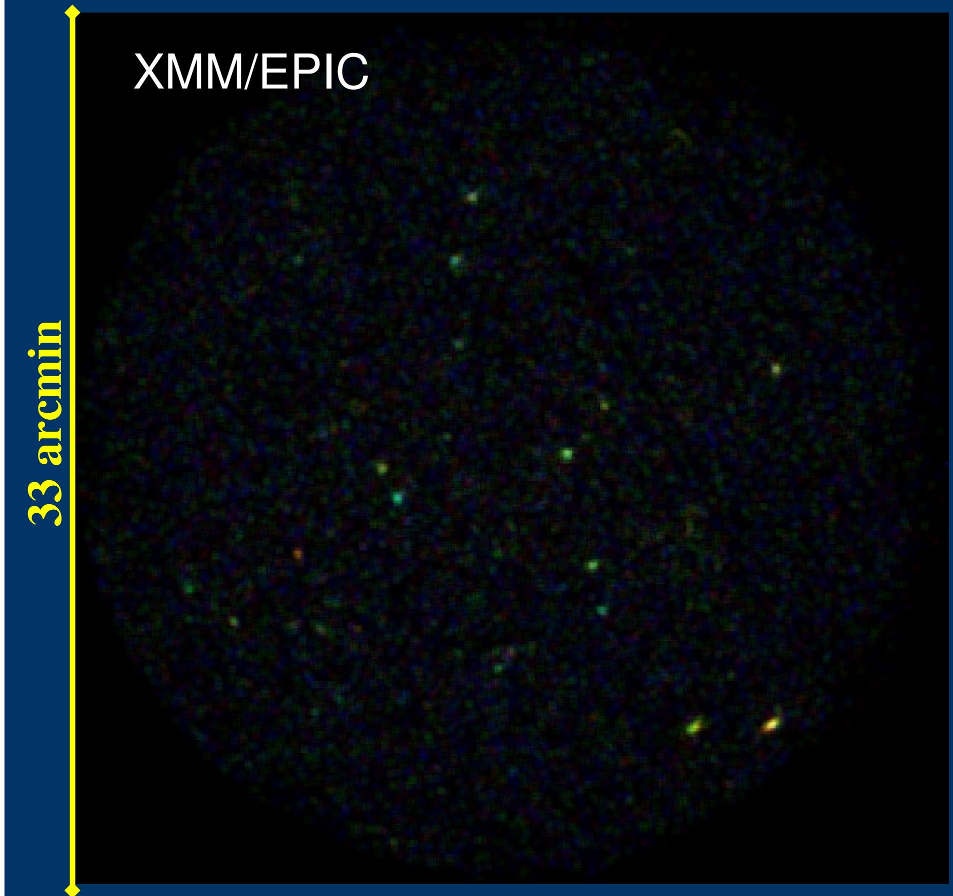
Optical Data Analysis

- Optical data reduction with the THELI pipeline:
  - Basic Reduction (chip by chip on parallel CPUs)
  - Astrometric Calibration→ Distorsion Map → Distorsion Correction
  - Image Stacking, CR rejection
  - Exposure Map Correction
  - Photometric Calibration

- Catalogue production using tools developed in the ESO Imaging Survey
  - Object Extraction → Single-Bands Catalogues
  - Multi-Band WFI Catalogues
  - Multi-Band WFI + 2MASS and *GSC2*

Field	U		N
1			5688
2			20837
3			32202
4			34093
5	-		11329
6	-		7423
7	-		6820
8	-		15578

red = 0.3-1 keV
green = 1-3 keV
blue = 3-10 keV



red = R band
green = V band
blue = B band

The Strategy

- Automatic Optical Classification

•Model SEDs library (stars, galaxies)
•Convolution with band response → Simulated magnitudes
•Interstellar Extinction evaluation (Schlegel maps)
•Simulated vs Observed magnitudes → Optical Classification

- X-ray vs Optical Multi-Band Catalogues Matching

- X-ray Source Classification

•Fx/Fopt → Distinctive of X-ray Source Class
•HRs → Distinctive of X-ray Source Class
•X-rays + Optical Classifications
•Information passed to a Decision -Tree Algorithm

← Still to be fine-tuned

X-ray/Optical Cross-Correlations

	Obs. ID	Detected Sources	X–ray sources with counterpart	Candidate Counterparts	Reliability (1-P)
	1	50	23	26	84 %
3EG 0616-3310	2	37	30	46	76 %
	3	32	25	41	82 %
	4	27	24	40	70 %
	Total	146	102	153	-
	5	38	20	21	71 %
3EG 1249-8330	6	51	17	19	80 %
	7	7	2	2	81 %
	8	52	28	37	76 %
	Total	148	67	79	-

Optical coverage less deep for 3EG1249-8330 than for 3EG 0616-3310

$$P = 1 - e^{-\pi r^2 \mu}$$

r = cross-correlation radius = 5″

μ = objects surface density per sq. degree

16% < P < 30% → chanche coincidence contamination significant

The F_x/F_{opt} ratio Classification Scheme

$$\frac{f_{X,\mathrm{XMM}}}{f_B} = \frac{f_{X,\mathrm{Hamburg-RASS}}}{f_B} \times$$

$$\frac{f_{X,\mathrm{XMM}}}{f_{X,\mathrm{Hamburg-RASS}}} = \frac{f_{0.3-10,\mathrm{PL}}}{f_{0.1-2.4,\mathrm{MOD}}} = \frac{f_{0.3-10,\mathrm{PL}}}{f_{0.1-2.4,\mathrm{PL}}} \times \frac{cf_{0.1-2.4,\mathrm{PL}}}{cf_{0.1-2.4,\mathrm{MOD}}}$$

CR-Flux conversion

$$\frac{f_{X,\mathrm{XMM}}}{f_{B_J}} = \frac{f_{X,\mathrm{XMM}}}{f_B} \times$$

$$\frac{f_B}{f_{B_J}} = \frac{f_{B,\mathrm{Vega}}}{f_{B_J,\mathrm{Vega}}} \times 10^{-(B-B_J)/2.5} = 0.822 \times 10^{-(B-B_J)/2.5}$$

Flux conversion

F_X/F_B

Obs. ID	Stars	WDs	CVs	Galaxies	Clusters	AGN
1	-4.19/−0.43	+0.74/+2.65	-1.33/+1.31	-0.81/+1.72	+0.13/+1.91	-0.02/+1.70
2	-4.19/−0.43	+0.73/+2.64	-1.33/+1.30	-0.81/+1.72	+0.12/+1.91	0/+1.71
3	-4.21/−0.41	+0.69/+2.59	-1.35/+1.28	-0.82/+1.71	+0.13/+1.91	-0.04/+1.68
4	-4.23/−0.39	+0.64/+2.55	-1.37/+1.27	-0.82/+1.71	+0.13/+1.91	-0.05/+1.67
5	-4.08/−0.54	+0.85/+2.76	-1.22/+1.41	-0.70/+1.83	+0.23/+2.01	+0.09/+1.81
6	-4.09/−0.53	+0.85/+2.75	-1.24/+1.40	-0.72/+1.81	+0.21/+2.00	+0.07/+1.79
7	-4.13/−0.49	+0.78/+2.68	-1.27/+1.37	-0.73/+1.80	+0.21/+2.00	+0.05/+1.77
8	-4.07/−0.55	+0.87/+2.77	-1.21/+1.43	-0.69/+1.84	+0.24/+2.03	+0.10/+1.82

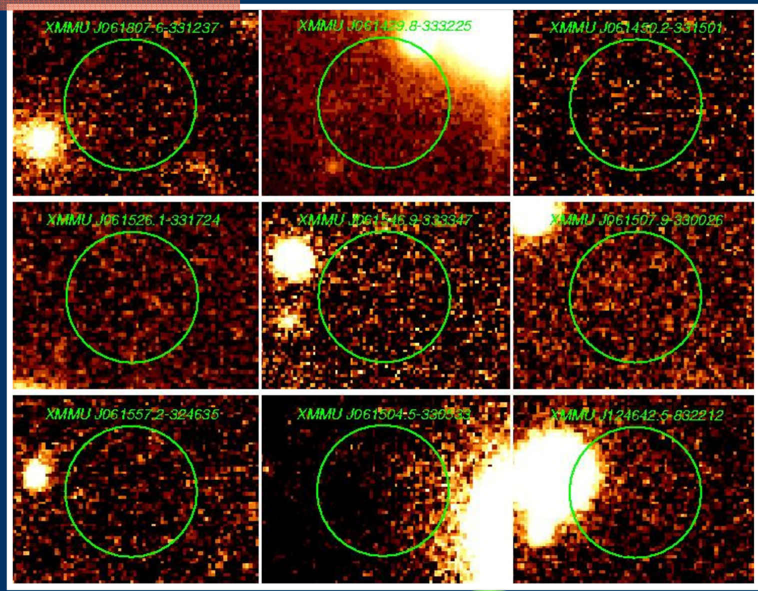
F_X/F_{BJ}

Obs. ID	Stars	WDs	CVs	Galaxies	Clusters	AGN
1	-3.90/−0.50	+1.00/+2.70	-1.02/+1.42	-0.54/+1.83	+0.38/+2.11	+0.25/+1.72
2	-3.91/−0.49	+0.99/+2.69	-1.02/+1.41	-0.54/+1.83	+0.37/+2.10	+0.26/+1.73
3	-3.93/−0.47	+0.95/+2.65	-1.04/+1.39	-0.55/+1.82	+0.38/+2.11	+0.23/+1.70
4	-3.94/−0.45	+0.89/+2.60	-1.06/+1.38	-0.56/+1.81	+0.38/+2.11	+0.22/+1.69
5	-3.80/−0.60	+1.11/+2.81	-0.91/+1.52	-0.44/+1.94	+0.48/+2.21	+0.35/+1.82
6	-3.81/−0.59	+1.10/+2.80	-0.92/+1.51	-0.45/+1.92	+0.46/+2.19	+0.34/+1.81
7	-3.84/−0.56	+1.04/+2.74	-0.96/+1.48	-0.47/+1.91	+0.46/+2.20	+0.32/+1.78
8	-3.78/−0.62	+1.12/+2.82	-0.90/+1.54	-0.42/+1.95	+0.49/+2.22	+0.37/+1.84

Candidates Selection

- 125 X-ray sources with no optical counterpart selected.

  "Cesarean Cut" approach



- 9 X-ray sources with $F_x/F_{opt} > 100$

- F_x/F_{opt} → no stars, no AGNs, no galaxies, no XRBs → hot stars (i.e. possible NSs)

+

- 8 X-ray sources with softer spectra, i.e. KT<0.5 keV and/or detected <1 keV only

↓

- Possible Geminga-like INS candidates

Summary

- 3EG 0616-3310:
- About 30% have no optical counterpart down to V~24.5
- 8 X-ray sources with Fx/Fopt > 100
- 5 X-ray sources with a soft thermal spectrum
- One X-ray source with both Fx/Fopt > 100 and a soft thermal spectrum

- 3EG 1249-8330:
- About 55% have no optical counterpart down to V~24.5
- 1 X-ray source with Fx/Fopt > 100
- 3 X-ray sources with a soft thermal spectrum

- Best candidates sorted according to Fx/Fopt

→XMMU J061429.8-333225 for 3EG 0616-3310

→XMMU J124642.5-832212 for 3EG 1249-8330

- La Palombara, Mignani et al. (2006) – A&A, in press - Presented at "*The Multi-Messenger Approach to High Energy Gamma-Ray Sources*", held in Barcelona, July 4th – 7th
- Deep follow-up XMM investigation of UGO candidate counterparts in progress (timing, spectroscopy)

Future Work (i)

- Extend the work to other selected EGRET UGOs

  - Large program → More targets → More data → More efficiency

- Exploit public X-ray archives and catalogues with their built-in XIDs

  - X-ray pointings may easily overlap partially but not cover completely a whole EGRET error box

  - Selection by instrument mode to maximize FOV reduces the useful data set

- Exploit public optical archives (e.g. ESO, CADC)

  - Probability of finding optical data which (by chanche) overlap with an X-ray field which (by chanche) overlap with an EGRET error box is likely very small

  - Color coverage, critical for object classification, may not be adequate

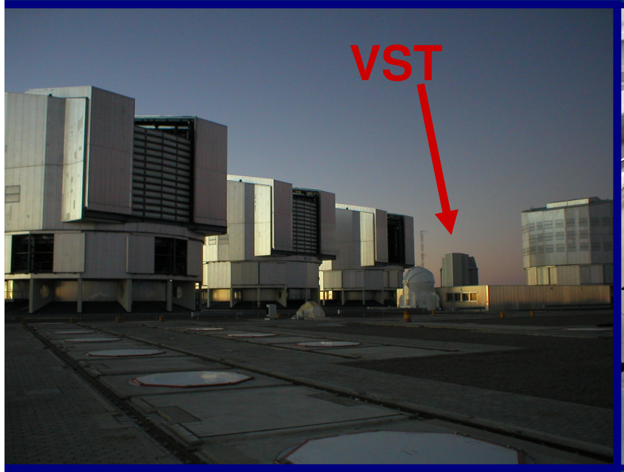
  - FOVs of optical imaging devices is generally small (< 10x10 arcmin)

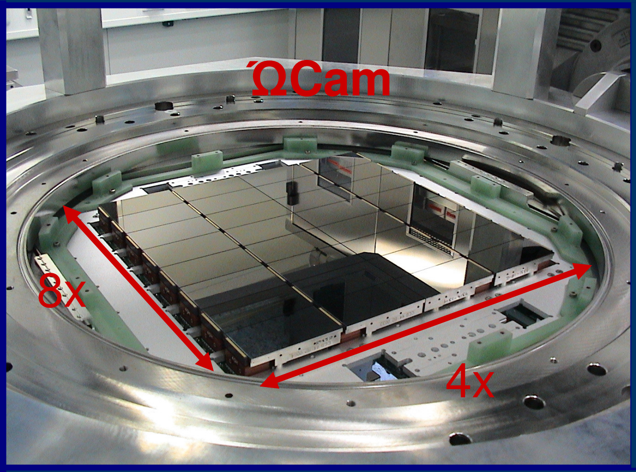
- Exploit existing public CCD surveys (e.g. the SDSS)

  - Sky coverage limited to selected sky areas

Future Work (ii)

- Exploit new/future wide field optical/IR facilities.
  - MegaCam@CFHT, a 5x8 CCDs 1x1 deg optical/IR imaging camera
  - VST, a 2.5m ESO survey telescope equipped with the 4x8 CCDs 1x1 deg ΩCam (to be commissioned by Q4 2006)
  - VISTA, a 4m UK/ESO survey telescope with a 4x4 chip 1x1 deg IR detectors array (to be commissioned by Q2 2007)
  - ≈ 4x WFI





- Improve data processing/analysis
  - Data processing with parallel CPUs on Beowulf-like clusters
  - Smarter automatic classification algorithms (self learning by training sets)

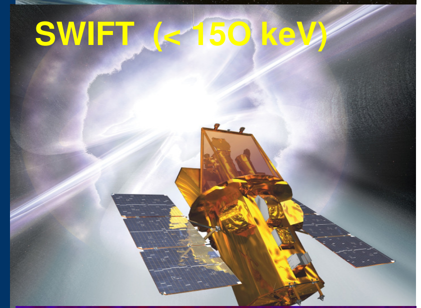
Future Work (iii)

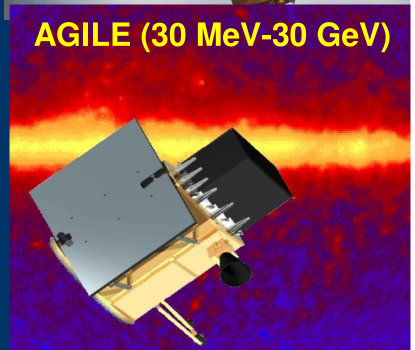
- The 3rd GRO/EGRET catalogue is still the reference
- No High Energy Gamma-ray coverage currently flying
- Wait for upcoming gamma-ray satellites

•AGILE (*Astrorivelatore **G**amma ad **I**mmagini **LE**ggero)*
•To be launched in 2006
•0.3° positioning, 60 deg f.o.v, sensitivity ≈ GRO/EGRET

•GLAST (*Gamma-ray **L**arge **A**rea **S**pace **T**elescope)*
•To be launched by Q3 2007
• 0.15 °positioning, 2.5 sr f.o.v., sensitivity: x50 GRO/EGRET

•Better statistics → improved timing and spectral analysis
•Better positioning → XMM follow-ups, one pointing only
→ x4 more efficient OR x2 deeper
→ VLT follow-ups, tighter Fx/Fopt
•More straight UGO identification





Conclusions